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CONSTRAINING CP-VIOLATING TGCS AND MEASURING W-POLARIZATION AT OPAL

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A measurement of the polarization of W bosons in semi-leptonically decaying W pairs produced at 189 GeV is presented. Rates of longitudinally and transversely polarized W bosons and correlation between two W bosons are studied. The spin properties of the leptonically decaying W boson in the W pairs was used to measure the CP-violating trilinear gauge boson couplings. These results are compared with Standard Model expectations.

1 The Spin Density Matrix for $\mathrm{W^+W^-}$

Polarization properties of $\mathrm{W^+W^-}$ produced in $\mathrm{e^+e^-}$ collisions are summarized by the two-particle joint spin density matrix (SDM). The SDM is the product of the amplitudes for producing a $\mathrm{W^+}$ and $\mathrm{W^-}$ of respective helicities τ_+, τ_-:

$$\rho_{\tau_- \tau'_- \tau_+ \tau'_+}(s, \cos\theta_{\mathrm{W}}) = \frac{\sum_\lambda F^{(\lambda)}_{\tau_-\tau_+} (F^{(\lambda)}_{\tau'_-\tau'_+})^*}{\sum_{\lambda\tau_+\tau_-} |F^{(\lambda)}_{\tau_-\tau_+}|^2} \, . \tag{1}$$

The diagonal elements are probabilities of producing $\mathrm{W^+W^-}$ with the corresponding helicity combinations, and are strictly real. The potentially complex off-diagonal terms represent interference between helicity states. The data considered in the analysis were collected with the OPAL detector in 1998, at a centre-of-mass energy of 189 GeV. They correspond to an integrated luminosity of $\sim 183\ \mathrm{pb}^{-1}$, with 1065 events identified as $\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}}\ell\nu$. Only semi-leptonic decays are used for this analysis, as fully leptonic and fully hadronic decays cannot be unambiguously reconstructed. Due to the restricted sample size, it is not possible to measure all 81 elements of the joint SDM; however, all elements of the nine-element single-particle SDM, obtained by summing over the helicity states of the $\mathrm{W^+}$, may be measured:

$$\rho^{W^-}_{\tau_-\tau'_-}(s, \cos\theta_{\mathrm{W}}) = \sum_{\tau_+} \rho_{\tau_-\tau'_-\tau_+\tau_+}(s, \cos\theta_{\mathrm{W}}) \, . \tag{2}$$

Its diagonal elements are the probabilities of producing a $\mathrm{W^-}$ with helicity $+1, 0$ or -1. In order to use both $\mathrm{q\bar{q}}\ell^-\bar{\nu}$ and $\mathrm{q\bar{q}}\ell^+\nu$, CPT is assumed.

The five kinematic variables used in the analysis are the cosine of the polar production angle of the $\mathrm{W^-}$ in the laboratory frame ($\cos\theta_W$), and the decay

angles given by the directions of the fermion and anti-fermion with respect to the W^+ and W^- respectively in the W rest-frames ($\cos\theta^*_\ell, \phi^*_\ell, \cos\theta^*_j, \phi^*_j$), with an ambiguity of π for both jet angles due to the difficulty of distinguishing the up-quark jet from the anti–down-quark jet. With the hadronic part of the event, it is therefore only possible to measure combinations of SDM elements which are symmetric under $\cos\theta^* \to -\cos\theta^*$ and $\phi^* \to \phi^* + \pi$. Fortunately, these include $\rho_{++} + \rho_{--}$ and ρ_{00}, so the full two-particle SDM element ρ_{0000} and the combinations $\rho_{++++} + \rho_{++--} + \rho_{--++} + \rho_{----}$ and $\rho_{++00} + \rho_{--00} + \rho_{00++} + \rho_{00--}$ may be measured.

SDM elements are measured by forming histograms of the $\cos\theta_W$ distribution obtained in the data, and weighting each event by a projection operator which is a function of $\cos\theta^*_\ell, \phi^*_\ell, \cos\theta^*_j, \phi^*_j$. Different operators project out each independent element of the SDM. Results are shown in figure 1.

Constraints arise from imposing tree-level CPT-invariance:

$$\mathrm{Re}(\rho^{W^-}_{\tau_1\tau_2}) - \mathrm{Re}(\rho^{W^+}_{-\tau_1-\tau_2}) = 0 \tag{3}$$

$$\mathrm{Im}(\rho^{W^-}_{\tau_1\tau_2}) + \mathrm{Im}(\rho^{W^+}_{-\tau_1-\tau_2}) = 0\,. \tag{4}$$

Since CPT has already been assumed, any deviation from these must arise from loop effects. CP-invariance would further imply that:

$$\mathrm{Im}(\rho^{W^-}_{\tau_1\tau_2}) - \mathrm{Im}(\rho^{W^+}_{-\tau_1-\tau_2}) = 0\,. \tag{5}$$

Combining equations 4 and 5 shows that all single-particle SDM coefficients must be strictly real in the absence of CP-violation.

2 Helicity Cross-Sections

Differential production cross-sections for $W^\pm$ of particular helicities are:

$$\frac{\mathrm{d}\sigma_h}{\mathrm{d}\cos\theta_\mathrm{W}} = f_h \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_\mathrm{W}}\,, \tag{6}$$

where $f_\mathrm{T} = \rho_{++} + \rho_{--}$, $f_\mathrm{L} = \rho_{00}$, $f_\mathrm{TT} = \rho_{++++} + \rho_{++--} + \rho_{--++} + \rho_{----}$, $f_\mathrm{LL} = \rho_{0000}$, $f_\mathrm{TL} = \rho_{++00} + \rho_{--00} + \rho_{00++} + \rho_{00--}$. Corresponding total cross-sections may be obtained by integrating over the full range of $\mathrm{d}\cos\theta_\mathrm{W}$. Results are given in table 1. Correction factors are included for detector and reconstruction effects. The W^+ and W^- polarizations are about 7% correlated. This effect is included in the systematic errors. Total cross-sections for the various helicity states are very strongly correlated. It should be noted that ρ_{0000} can have no CP-violating contributions,[1] and $\frac{\mathrm{d}\sigma_\mathrm{LL}}{\mathrm{d}\cos\theta_\mathrm{W}}$ is thus completely insensitive to CP-violation. The helicity fractions for TT, LL

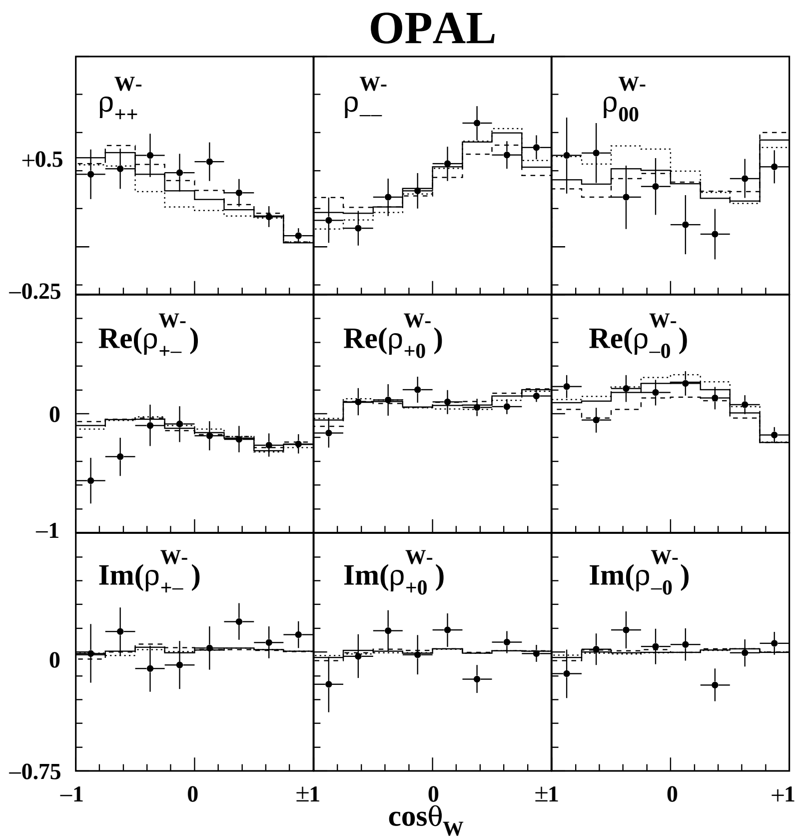

Figure 1. SDM elements from leptonically decaying W bosons in $qq\ell\nu$ data events. Points are OPAL data, with statistical and systematic errors. Histograms show Monte Carlo predictions with full detector simulation. The solid line shows the SM expectation and the dotted (dashed) line that for $\Delta g_1^z = +0.5$ (-0.5).

and TL differ by about 2σ from Standard Model (SM) predictions, giving a χ^2 probability of about 10% for SM compatibility.

	Data	SM Exp.
$\sigma_{\mathrm{T}}/\sigma_{\mathrm{total}}$		
W$\rightarrow \ell\nu$	$0.842 \pm 0.048 \pm 0.023$	0.746 ± 0.006
W$\rightarrow$ qq	$0.738 \pm 0.045 \pm 0.025$	0.741 ± 0.006
All	$0.790 \pm 0.033 \pm 0.016$	0.743 ± 0.004
$\sigma_{\mathrm{L}}/\sigma_{\mathrm{total}}$		
W$\rightarrow \ell\nu$	$0.158 \pm 0.048 \pm 0.023$	0.254 ± 0.006
W$\rightarrow$ qq	$0.262 \pm 0.045 \pm 0.025$	0.259 ± 0.006
All	$0.210 \pm 0.033 \pm 0.016$	0.257 ± 0.004

	Measured	Expected
$\sigma_{\mathrm{TT}}/\sigma_{\mathrm{total}}$	$0.781 \pm 0.090 \pm 0.033$	0.572 ± 0.010
$\sigma_{\mathrm{LL}}/\sigma_{\mathrm{total}}$	$0.201 \pm 0.072 \pm 0.018$	0.086 ± 0.008
$\sigma_{\mathrm{TL}}/\sigma_{\mathrm{total}}$	$0.018 \pm 0.147 \pm 0.038$	0.342 ± 0.016

Table 1. Fractions of W polarizations, and of W^+W^- pairs of each helicity combination. Expected values are from generator level EXCALIBUR Monte Carlo.

3 Triple Gauge Boson Couplings

Of nine possible W^+W^- helicity pairings, seven are allowed in the s-channel processes $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow W^+W^-$ ($+-$, $-+$ occur only in t-channel ν-exchange, as $|\tau_+ - \tau_-| = 2$). There are then seven free parameters in the Lagrangian describing each of the triple gauge boson couplings $W^+W^-Z^0$ and $W^+W^-\gamma$, here called $\kappa_V, g_1^V, \lambda_V, g_5^V, \tilde{\kappa}_V, g_4^V, \tilde{\lambda}_V$ ($V = Z^0, \gamma$). The first two are unity in the SM, and the others zero. The first three conserve C and P, g_5^V violates C and P but conserves CP, and the last three violate CP.

The real elements of the SDM are sensitive to all of the coupling parameters; the imaginary elements are also sensitive to CP-violating parameters. It is impossible to fit all fourteen parameters simultaneously with the limited data sample. Each is measured separately, with the others set to their SM values, except those related to the tested parameter through $SU(2) \times U(1)$ symmetry[2] ($\tilde{\kappa}_Z = -\tan^2\theta_W \tilde{\kappa}_\gamma$; $\tilde{\lambda}_Z = \tilde{\lambda}_\gamma$; $g_4^Z = g_4^\gamma$). This leaves three independent parameters to test, chosen to be $\tilde{\kappa}_Z, \tilde{\lambda}_Z, g_4^Z$. There are strong constraints on CP-violation in electromagnetic interactions from the constraints on the electric dipole moment of the neutron,[3] which is why an alternative would be to ignore the gauge symmetry constraints and set $W^+W^-\gamma$ couplings to zero. Coupling values from a fit to the SDM elements are given in table 2. Table 2 also includes results from a χ^2 fit to the $\cos\theta_W$ distribution.

Fit	$\tilde{\kappa}_{\mathrm{z}}$	g_4^{z}	$\tilde{\lambda}_{\mathrm{z}}$
SDM Elements	$-0.19^{+0.08}_{-0.07}$	$0.00^{+0.21}_{-0.20}$	$-0.12^{+0.17}_{-0.16}$
$\cos\theta_{\mathrm{W}}$	$-0.19^{+0.46}_{-0.08}$	$0.7^{+0.4}_{-1.8}$	$-0.29^{+0.69}_{-0.11}$
Combined	$-0.19^{+0.06}_{-0.05}$	$0.01^{+0.22}_{-0.22}$	$-0.19^{+0.18}_{-0.13}$
Expected Stat. Error	± 0.11	± 0.19	± 0.12
Final Fit Including Systematics	$-0.20^{+0.10}_{-0.07}$	$-0.02^{+0.32}_{-0.33}$	$-0.18^{+0.24}_{-0.16}$

Table 2. Measured values of CP-violating TGC parameters. Both the SDM elements and the $\cos\theta_{\mathrm{W}}$ production distribution are used in the calculation. Errors are statistical only except in the case of the final combined fit.

The $\cos\theta_W$ distribution is the most sensitive to variations in CP-conserving couplings, but is relatively insensitive to CP-violating couplings. Figure 2 shows χ^2 curves for TGCs measured from SDM elements and from $\cos\theta_W$ distributions. The real SDM elements and $\cos\theta_W$ are sensitive only to the magnitude of CP-violating couplings (their dependence on the couplings is quadratic), and so have a double minimum. The imaginary SDM elements depend linearly on the CP-violating couplings and can thus lift the degeneracy. The CP-conserving couplings measured from the SDM elements are fully compatible with the results of the OPAL optimal observable analysis.[4]

4 Conclusions

The SDM method allows direct measurement of the fraction of W bosons produced with longitudinal polarization. This longitudinal component of the W is a result of the electroweak symmetry breaking mechanism. It also provides constraints on CP-violation in TGCs. All results are compatible with SM predictions. This analysis is more fully described elsewhere.[5]

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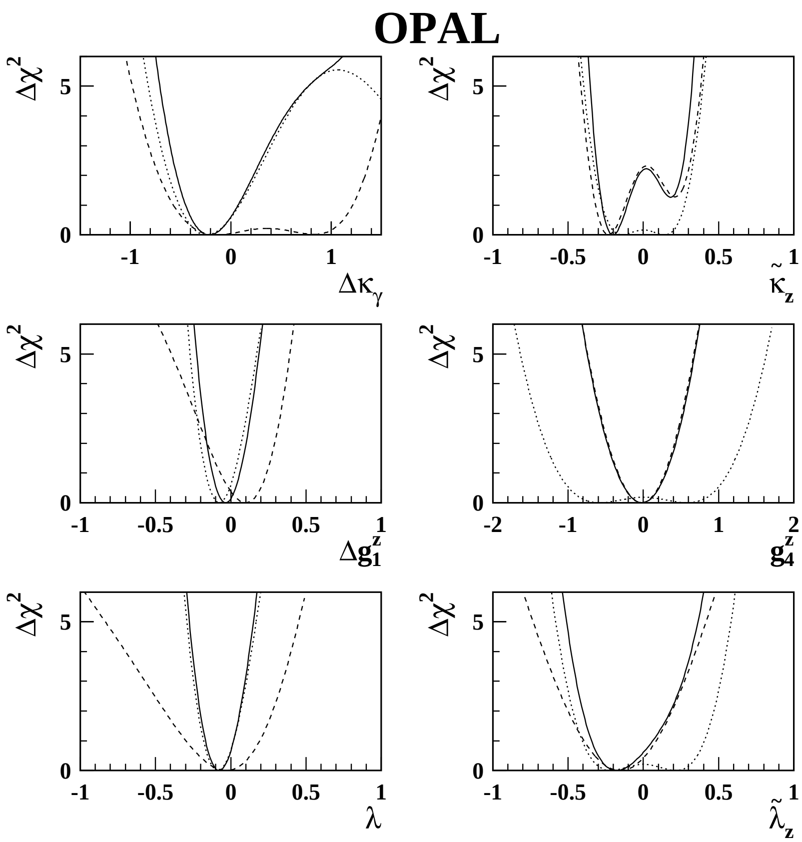

Figure 2. The χ^2 plots for the fits to the CP-conserving and CP-violating anomalous couplings. The dotted line is the fit to just the $\cos\theta_{\mathrm{W}}$ distribution. The solid line is the combined fit. All fits include systematic uncertainties.

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